Design of a Novel Mechanism for Actuation of a Bistable Buckled Beam

Saurav Kumar Dutta, B. Sandeep Reddy, and Santosha Kumar Dwivedy

Abstract The paper presents the design of a novel Scotch Yoke cum beam engine inspired mechanism to alternately actuate a bistable buckled beam between its two stable equilibrium states. The bistable buckled beam is used in a gripper of a pipe climbing robot with an inchworm motion. In the proposed mechanism, a beam engine is modified by replacing its crank with the crank of a Scotch Yoke and by putting additional links. The proposed mechanism gives a completely constrained one degree of freedom motion which can be driven by a single DC motor. The conceptual designs and models of the gripper and the pipe climbing robot are presented. The working of the proposed mechanism is checked and verified in Solidworks 2019.

Keywords Scotch Yoke · Beam engine · Pipe climbing robot · Pole climbing robot · Inchworm motion · Bistable compliant mechanism

1 Introduction

Bistable buckled beam is a type of bistable compliant mechanism. Complaint mechanisms are mechanisms which have flexible bars and flexible joints. These mechanisms are generally one-piece mechanisms and transfer energy through deformation and motion [1, 2]. A bistable compliant mechanism is one which has two stable equilibrium states in its range of motion [3, 4]. Generally, bistable compliant mechanisms are of two types. One is the bistable buckled beam [5, 6], and the other is bistable curved beam [7, 8]. A bistable buckled beam is realized by pre-buckling a straight column and then putting transverse loads on the buckled column so as to toggle it between the two stable equilibrium states. A bistable curved beam is one in which the beam is fabricated as the fundamental mode shape of the straight column buckling problem. Bistable compliant mechanisms are generally used in MEMS as micro-actuators, switches, micro-relays, micro-grippers and micro-valves

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[6–9]. They are also used for micromechanical non-volatile memory [10, 11], for morphing and aerospace applications [12–14], for energy harvesting [15–17] and in many consumer products [18]. The bistable compliant mechanisms are actuated between their two stable equilibrium states using shape memory alloys [14, 19–21], dielectric elastomer actuators [22], through pneumatic means [23, 24], piezoelectric actuators [25–27] and electro-thermal actuators [28, 29]. There are some bistable compliant mechanisms which are driven by the force of the user, like in the gripper of Balakuntala et al. [30]. The gripper has four arms which are attached on the bottom of a bistable shell. A switching mechanism, driven by the user opens the gripper. As the gripper makes contact with the object to be grasped, the gripper closes and comes back to its previous equilibrium state. Further, Sarojini et al. [31] developed a compliant sit-to-stand easy-chair. The proposed bistable mechanism is a two-port bistable mechanism. Port 1 force, used to switch the seat from one stable equilibrium state to the other stable equilibrium state, is obtained from the weight of the person, and port 2 force, used to move the seat back to the first stable equilibrium state, is applied using a lever attached to the armrests.

The last paragraph discusses the different applications of bistable compliant mechanisms and the different ways of actuating them. The actuation depends on the type of bistable compliant mechanism and its intended application. Hence, this paper proposes a Scotch Yoke cum beam engine inspired mechanism to alternately actuate a bistable buckled beam, which is used in a gripper for pipe or pole climbing applications. The paper has five sections. Section 2 introduces the model of the gripper for pipe or pole climbing. Section 3 presents the design of the proposed mechanism. Section 4 discusses the model of a pipe climbing robot along with the gripper and its actuating mechanism, and Sect. 5 concludes the paper.

2 Model of the Gripper

Figure 1 shows the three-dimensional (3D) computer aided design (CAD) model of the gripper. The gripper has been modelled in Solidworks 2019 by assuming that the gripper grips a pipe of 105–115 mm diameter. The gripper can grip pipes of other diameters also, but then, the gap between the plates clamping the beam and the plate for affixing the rubber pad has to be changed accordingly, as is evident from Fig. 1. This gap can be changed with the help of four nuts in each bolt. The beam shown in Fig. 1 is in unstressed state. It is stressed longitudinally only once in the beginning till it buckles. During this process, the nuts on one side of the beam are loosened and the beam can be stressed manually. Once the beam buckles, the loosened nuts are tightened and the beam remains in buckled state. Figure 2 shows the trimetric view of the gripper in ungripped and gripped positions. The bistable buckled beam can now be toggled between its two stable equilibrium states or between the gripped and ungripped positions by putting a transverse load on it. The next section discusses about a mechanical drive system which automates the toggling of the bistable buckled beam between its two stable equilibrium states.

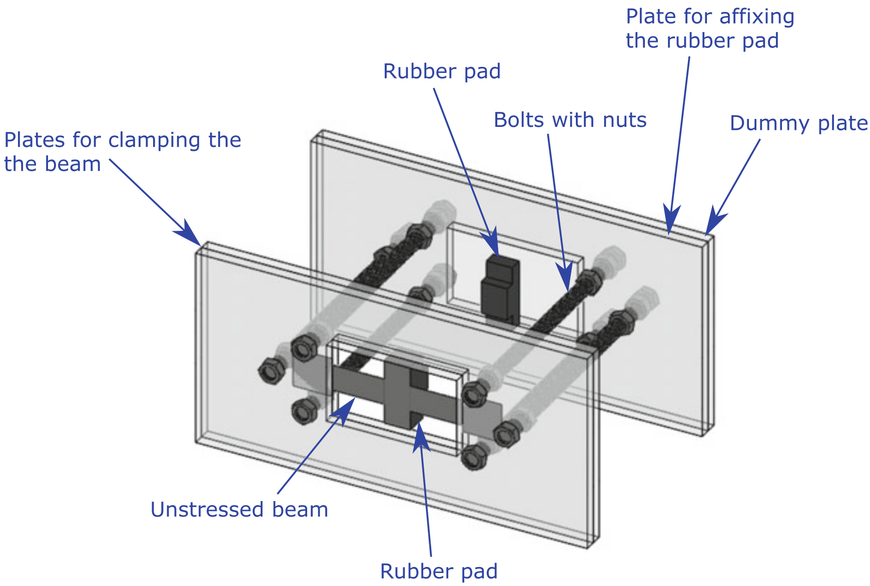


Fig. 1 Trimetric view of the 3D CAD model of the gripper

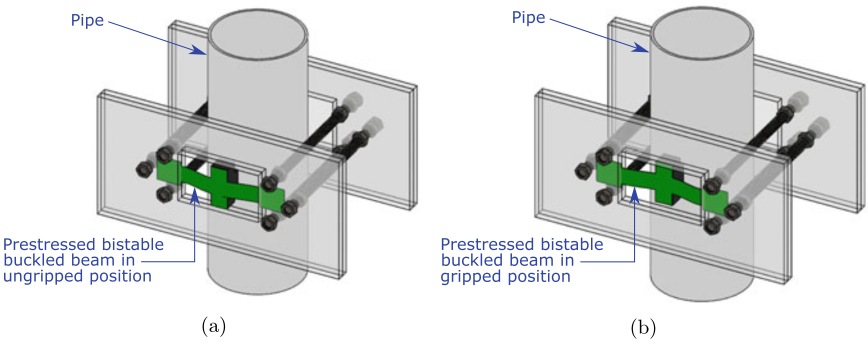


Fig. 2 Trimetric view of the gripper with pipe in **a** ungripped and **b** gripped positions

3 Design of the Actuating Mechanism

The toggling of the two stable equilibrium states of the bistable buckled beam can be automated by using two DC motors. The positions of actuation of the bistable buckled beam are shown in Fig. 3. In Fig. 3, point A corresponds to the central actuation of the bistable buckled beam and point B corresponds to the offset actuation of the bistable buckled beam. The actuator in point A takes the bistable buckled beam from its ungripped position to the gripped position, and the actuator in point B takes the

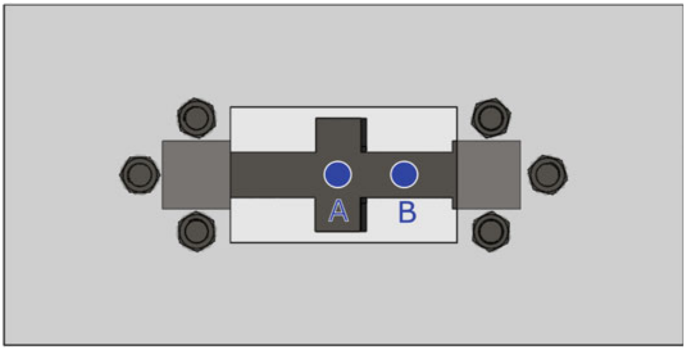


Fig. 3 Front view of the gripper with the actuation points

bistable buckled beam from its gripped position to the ungripped position. Two DC motors with translatory mechanisms could be placed in points A and B. However, to keep the gripper compact and the overall weight of the robot low, it is decided to use one motor for each gripper. Hence, a mechanism is designed by which the bistable buckled beam could be actuated alternately (point A for taking the buckled beam from ungripped to gripped position and point B for taking the buckled beam from gripped to ungripped position), by using a single DC motor.

The mechanism is modelled in Solidworks 2019, which ensures the alternate actuation of the bistable buckled beam using a single DC motor. The working of the proposed mechanism is checked using "animation, basic motion and motion analysis" options in Solidworks 2019. The proposed mechanism has completely constrained one degree freedom of motion. The mechanism shown in Fig. 4 has been modelled by combining the Scotch Yoke mechanism and a beam engine inspired mechanism. Scotch Yoke mechanism is one of the inversions of double slider crank chain [32], and beam engine is one of the inversions of four bar chain [33]. The proposed Scotch Yoke cum beam engine inspired mechanism involves only one DC motor and actuates the two positions (A and B) of the bistable buckled beam alternately. This is also evident from the plots of Fig. 5. From Fig. 5, it can be observed that the sliders of both the Scotch Yoke and the beam engine inspired mechanism operate alternately. The slider of the beam engine inspired mechanism actuates the point A, and the slider of the Scotch Yoke mechanism actuates the point B in the buckled beam through the lever, as can be seen in Fig. 4. Figures 5, 6 and 7 show the displacement versus time, velocity versus time and acceleration versus time plots, respectively, of the sliders of Scotch Yoke cum beam engine inspired mechanism. These plots have been obtained through motion analysis option in Solidworks. The dimensions of the proposed mechanism can be found in Fig. 8. The distance between the crank centre and the pin is 7 mm.

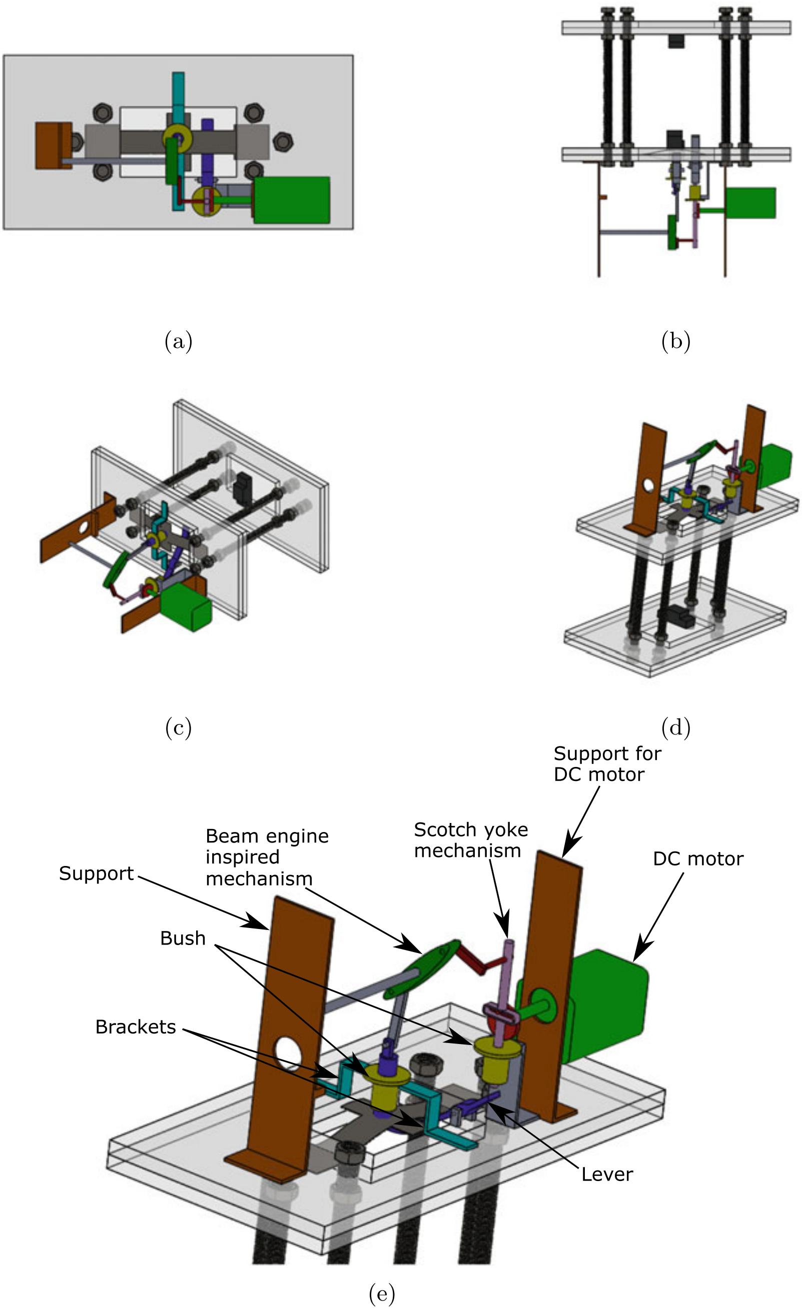
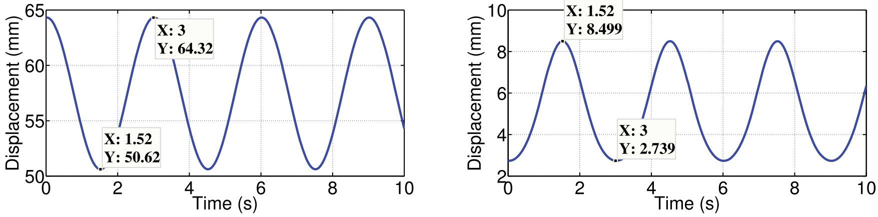
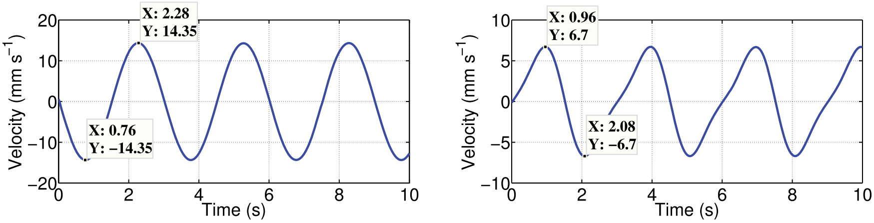


Fig. 4 **a** Front view, **b** top view, **c** isometric view and **d** a different view, **e** close up view of the gripper with the Scotch Yoke cum beam engine inspired actuating mechanism



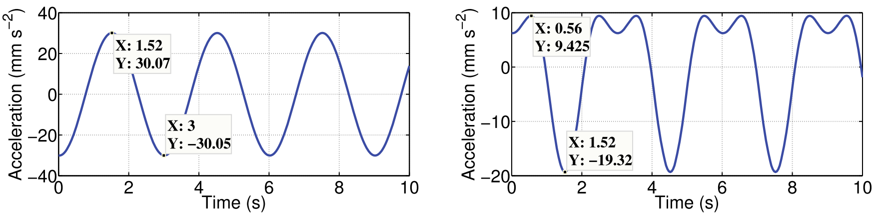
(a) (b)

Fig. 5 Displacement versus time plots of the slider of **a** Scotch Yoke mechanism and **b** beam engine inspired mechanism



(a) (b)

Fig. 6 Velocity versus time plots of the slider of **a** Scotch Yoke mechanism and **b** beam engine inspired mechanism



(a) (b)

Fig. 7 Acceleration versus time plots of the slider of **a** Scotch Yoke mechanism and **b** beam engine inspired mechanism

4 Model of the Pipe Climbing Robot

The gripper along with the proposed mechanism can be used in a pipe climbing robot with inchworm motion to automatically grip and ungrip pipes. Pipe climbing robots with inchworm motion can also be called as grasp-push-grasp motion [34] or clamp and push motion [35] or step-by-step motion [36]. The locomotion of a pipe climbing robot with inchworm locomotion is shown in Fig. 9.

The robot in Fig. 9 has two grippers, A and B. After assembling the robot around the pipe, the grippers A and B are in the clamped position at points 2 and 1, respec-

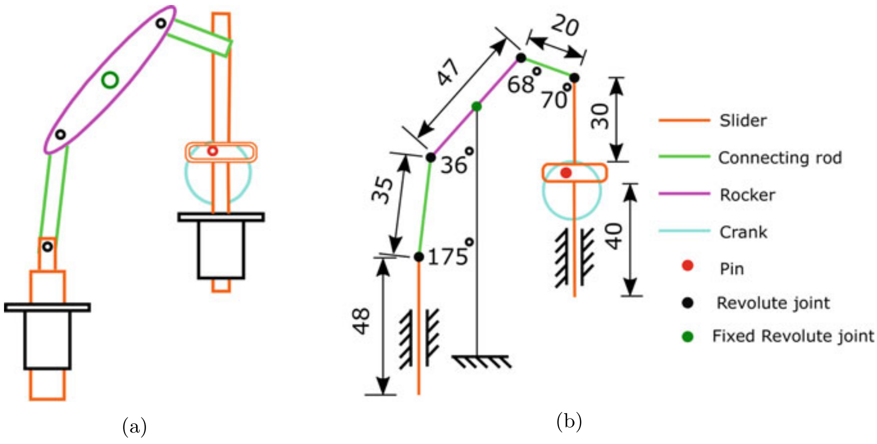


Fig. 8 **a** 2D schematic and **b** kinematic diagram of the proposed Scotch Yoke cum beam engine inspired mechanism

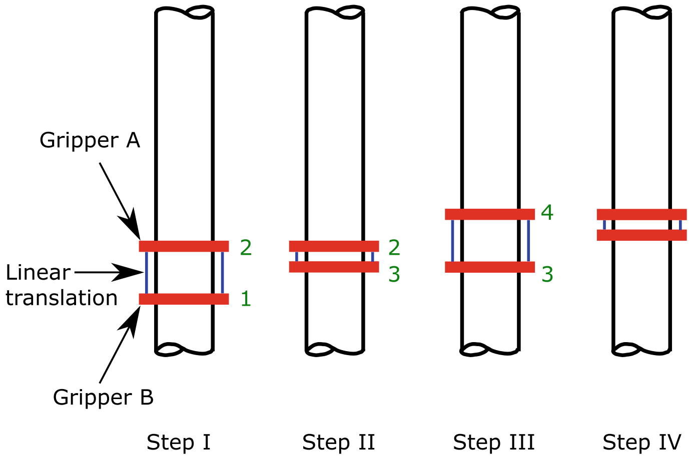
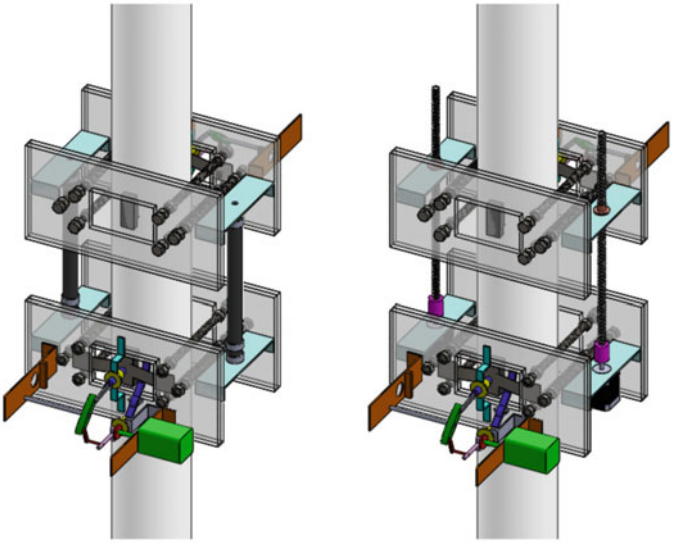


Fig. 9 Locomotion of an inchworm-type pipe climbing robot

tively. Gripper B is freed first, and then, a translational mechanism pulls it towards gripper A, up to point 3. Then, the gripper B is clamped at point 3 and gripper A is freed. The translational mechanism pushes gripper A away from gripper B up to point 4. Then, the gripper A is clamped at point 4 and the gripper B is again freed and pulled by the translational mechanism towards gripper A. This process repeats itself, thus resulting in climbing motion. The translational motion can be realized by an extensor contractor pneumatic artificial muscle, as shown in Fig. 10a or by using a stepper motor-driven lead screw, as shown in Fig. 10b. Information on pneumatic artificial muscle and extensor contractor pneumatic artificial muscle can be found in Refs. [37, 38], respectively.



(a) (b)

Fig. 10 Trimetric view of the 3D CAD model of the pipe climbing robot with **a** extensor contractor pneumatic artificial muscle and **b** stepper motor-driven lead screw

5 Conclusion

The paper proposes and designs a novel Scotch Yoke cum beam engine inspired mechanism for alternate actuation of a bistable buckled beam, used in a gripper for pipe climbing. The mechanism has been modelled and designed in Solidworks. After analysing the motion of the alternate actuation mechanism, the gripper is shown to be used in a pipe climbing robot by using either extensor contractor pneumatic artificial muscle or stepper motor-driven lead screw. Future work would be to carry out the kinetic analysis of the mechanism and to develop the pipe climbing robot.

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